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(54) **Optical waveguide having an intermediate layer**

(57) A waveguide comprises an organic substrate 2 e.g. of a polymer such as polycarbonate a waveguide layer 1 and an intermediate layer 8 which prevents a substantial amount of energy from penetrating into the relatively highly absorbent polymer material.

The waveguide material may be, for wavelengths of 400nm to 1000nm, TiO_2, TaO_5, ZrO_2, Al_2O_3, SiO_2-TiO_2, HfO_2, Y_2O_3, Nb_2O_5, silicon nitride, oxynitride (SiO_xN_y, HfO_xN_y, AlO_xN_y, TiO_xN_y, TaO_xN_y) and MgF_2 or CaF_2, and for wavelengths > 1000nm silicon, SiO_x, Ge, GaAs or GaAlAs.

The intermediate layer material, may be SiO_2, or an SiO_2, TiO_2-mixture or a material with Si_3N_4, such as Si_3N_4 or a mixture with Si_3N_4, and may be applied by a vacuum coating process.

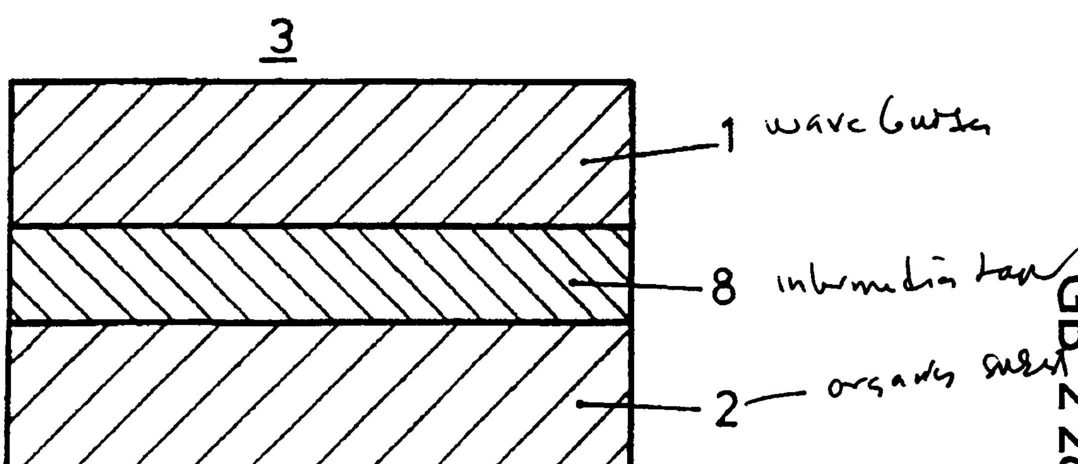

FIG. 9

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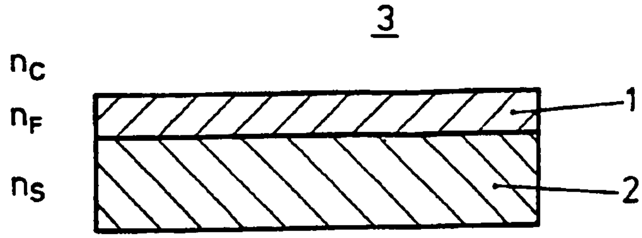

FIG. 1a

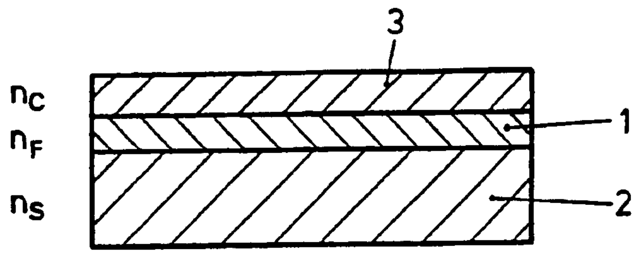

FIG. 1b

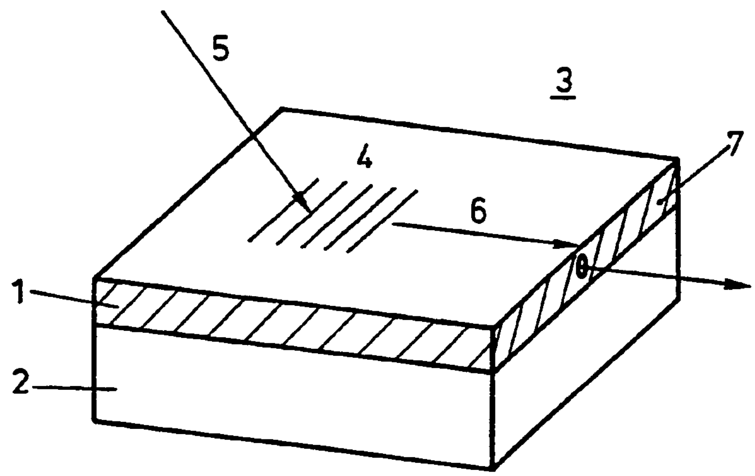

FIG. 2

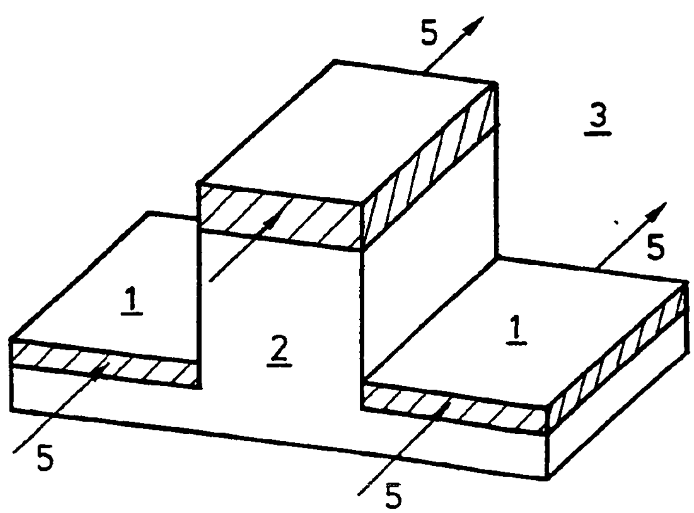

FIG. 3

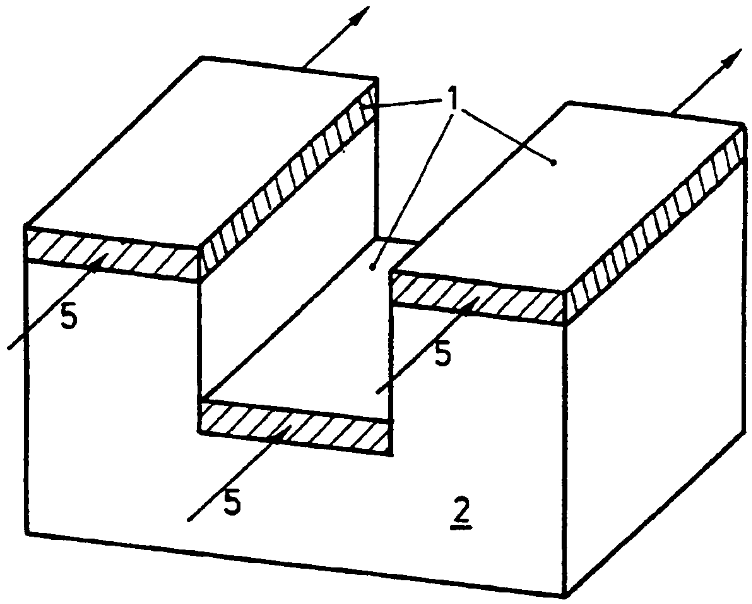

FIG. 4

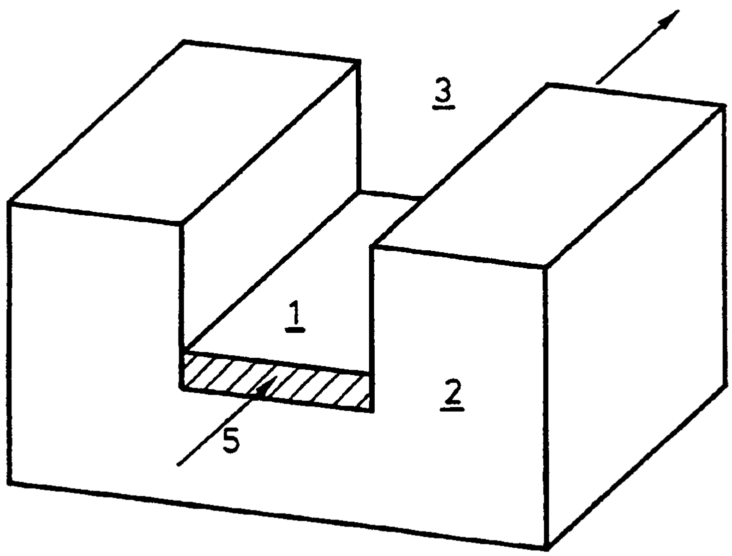

FIG. 5

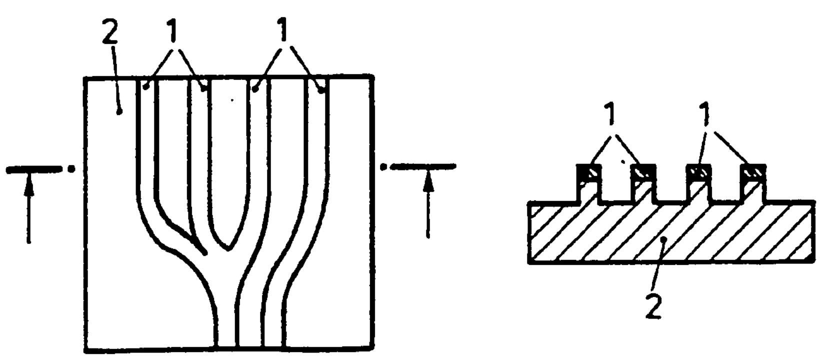

FIG. 6

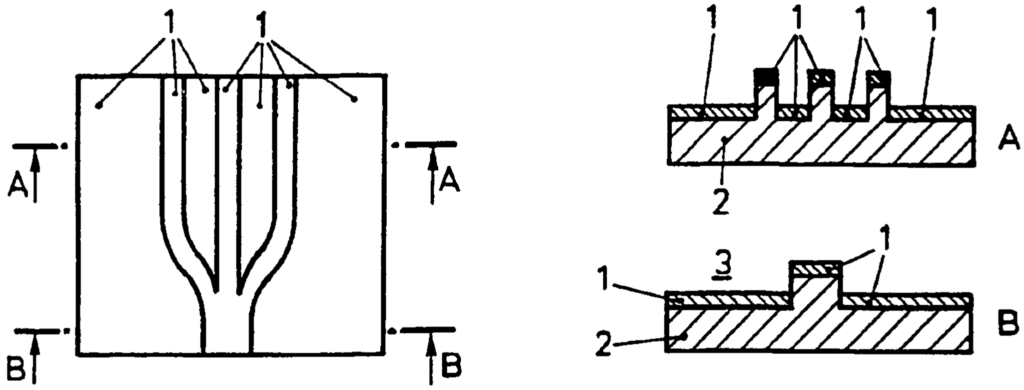

FIG. 7

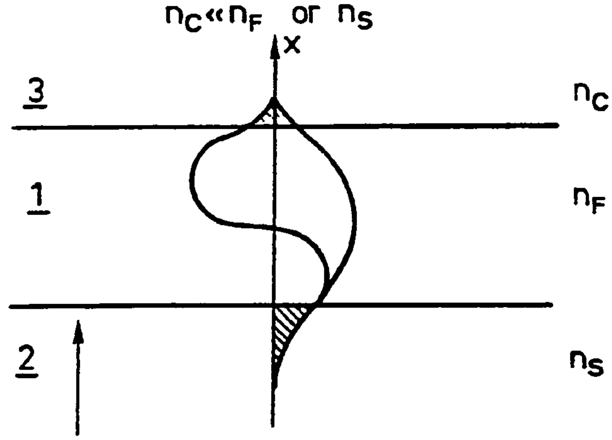

FIG. 8

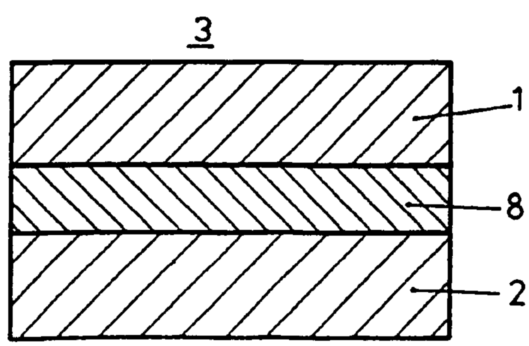

FIG. 9

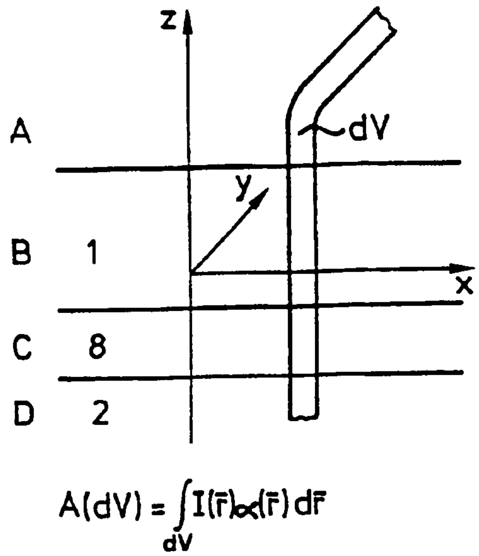

FIG.10

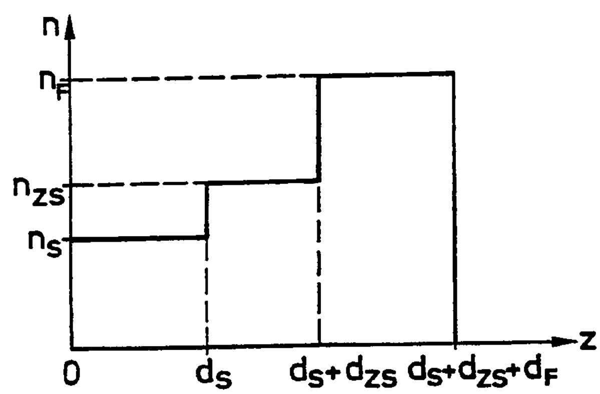

FIG. 11a

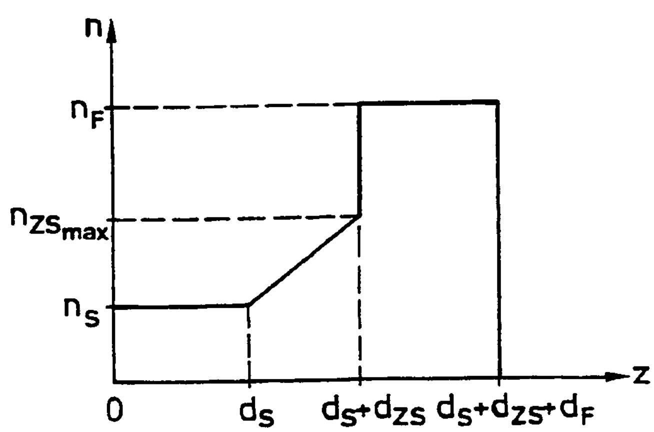

FIG.11b

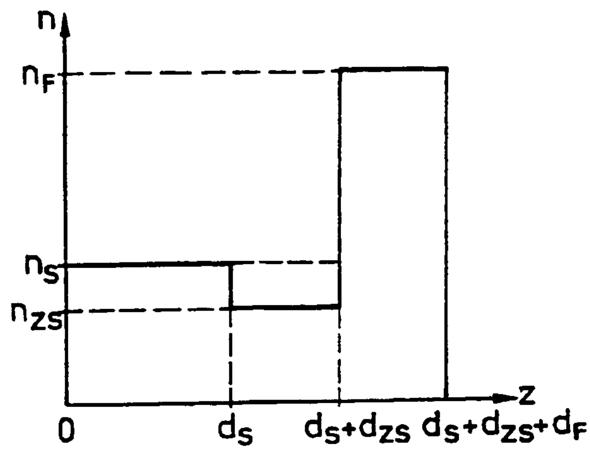

FIG.11c

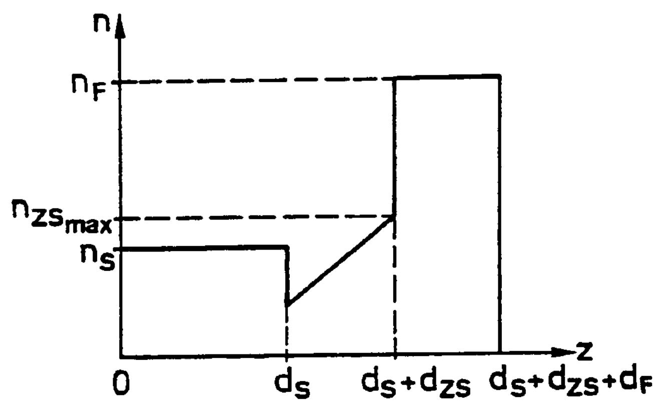

FIG.11d

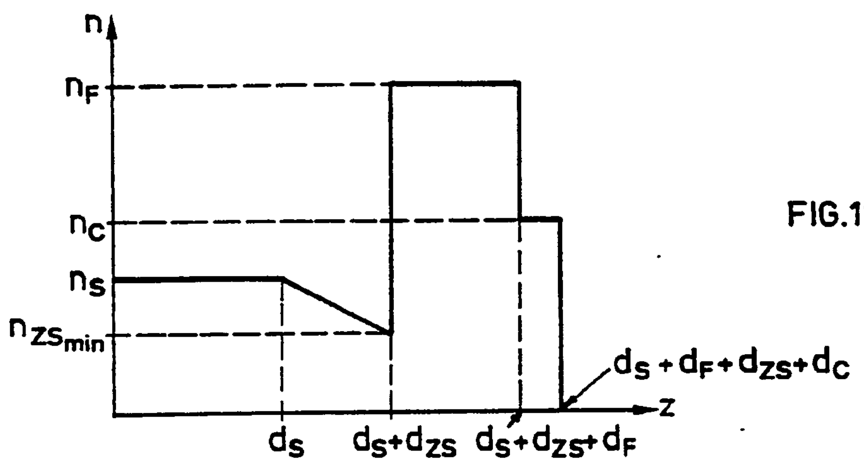

FIG.11e

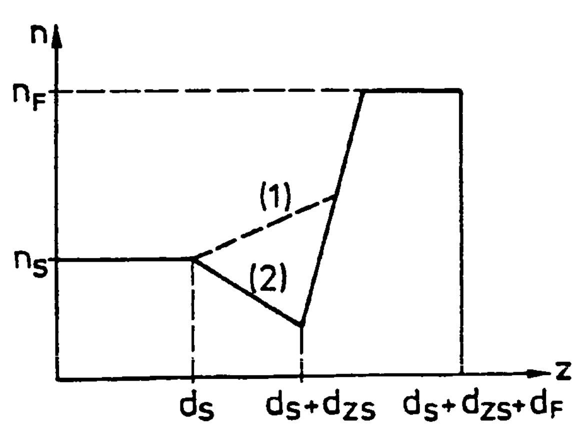

FIG.11f

1/Loss on PC
1/Loss auf PC

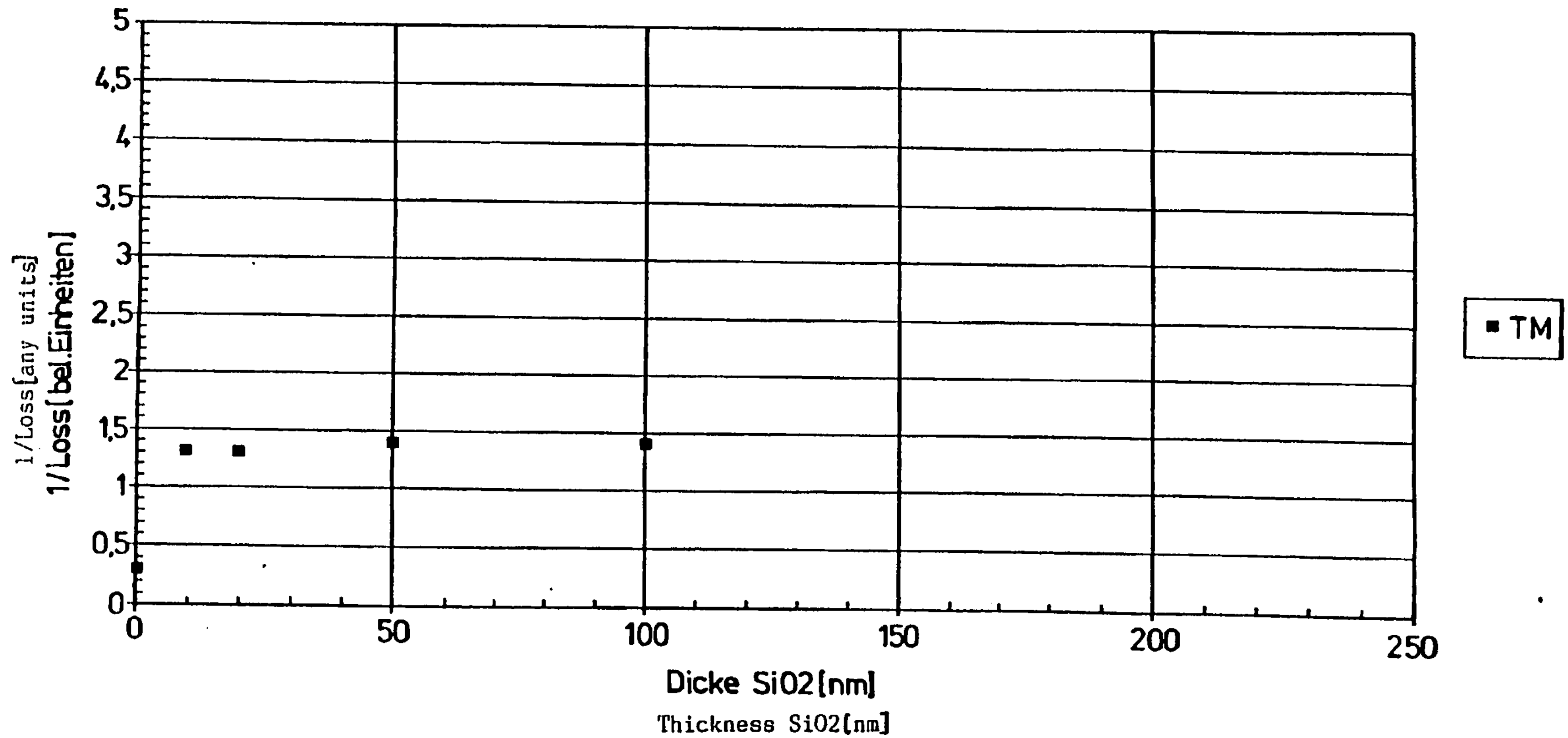

FIG.12

Waveguide and process for the production thereof

The present invention concerns a waveguide as set forth in the classifying portion of claim 1, a process for the production of a waveguide as set forth in claim 10, further a use of an intermediate layer on a waveguide as set forth in claim 15 and a use of an organic substrate as a carrier substrate on a waveguide as set forth in claim 16.

For many uses, for example sensors, integrated optics and the like it is desirable to have planar waveguides available. As shown in Figure 1a such a waveguide, in its simplest form, includes a waveguide layer 1 with a refractive index n_F on a substrate 2 with a refractive index n_S and an ambient medium 3, the so-called cover medium, or cover, with a refractive index n_C. The cover medium can in turn be formed by a layer or a layer system, as shown in Figure 1b. The following applies : $n_C < n_F$ and $n_S < n_F$.

For many uses at least one of those layers must be structured. In order for light to be coupled at all into the waveguide, the method which is in fact the most elegant method involves providing the waveguide with a structure 4 - a grating - , as shown in Figure 2a, and coupling the light 5, for example a laser beam, into the waveguide layer 1 by way of diffraction. If the coupling-in angle, grating period and waveguide layer thickness are suitably selected, the light 6 is propagated in the waveguide layer 1 with a given propagation mode and leaves the waveguide for example at an end face 7.

It is immaterial whether the grating 4 is provided at the substrate surface or in or at the waveguide layer.

In addition it is often desirable for the waveguide to be spatially structured as a whol . Figure 1b shows a waveguide without spatial structuring, Figures 3 and 4 show

structured strip-type waveguides and Figure 5 shows a buried strip-type waveguide. Figures 6 and 7 are a plan view and a view in section purely by way of xample of mor complex spatial structurings of a waveguide. Structured waveguides of that kind are widely used for example in the communications art or in the sensor art.

As waveguides of that kind are usually constructed on a glass substrate, the structuring procedures employed are photolithographic methods and the following etching methods: ion milling, reactive ion etching, wet-chemical etching and the like.

Such structuring procedures are time-consuming and expensive.

In addition waveguides on a glass substrate can only be shaped with difficulty and they are sensitive in regard to mechanical stresses such as impact stresses.

The substrate/waveguide layer/environment interaction but in particular the substrate/waveguide layer interaction which is relevant here substantially determines the waveguide property.

The problem of the present invention is to propose a waveguide :

a) in which structuring is substantially simpler and therefore less expensive and which possibly

b) is deformable within limits and/or

c) is less sensitive to mechanical stresses and/or

d) whose substrate can be used flexibly together with different waveguide layers and materials.

This is achieved in a waveguide of the kind set forth in th op ning part of this specification by th configuration thereof as set forth in the characterising portion of claim 1.

Particularly when using a polymer, such as for example and as is preferred nowadays a polycarbonate, as the waveguide substrate, it is now very much cheaper to structure the waveguide in particular as a whole, whether this is done by embossing, deep-drawing, injection moulding and the like, and then in particular to provide the coating with a wave-conducting material. In that respect it is found that the application of a wave-conducting material to a substrate of organic material, in particular a polymer, is in no way trivial. It is observed in particular that the losses of a waveguide produced in that way, that is to say waveguide layer directly on the substrate, defined as a drop in terms of intensity with a given mode and a given wave length over a certain distance, are substantially higher, at least by a factor of 10, than when an inorganic material such as for example glass is used as the substrate material.

To our knowledge the problem involved here is substantially new territory. Admittedly there are indications in the literature, for example in "Design of integrated optical couplers and interferometers suitable for low-cost mass production", R.E. Kunz and J.S. Gu, ECIO 93-Conferenz in Neuchâtel, that integrated optics could be inexpensively made from structured plastics material, but such reports can only document an existing need.

It is self-evident however that on the one hand all structuring procedures for organic materials, in particular polymers, and on the other hand coating processes such as CVD, PECVD, including vapour deposit, sputtering, ion plating, etc., belong to the state of the art. In that respect coating of plastics parts, for example spectacle lens s, reflectors etc. with very different materials also

b longs to th stat of the art, for example including by means of plasma polymerisation.

Attention should further be directed to the theory of planar waveguides in "Integrated Optics: Theory and Technology", R.G. Hunsperger, Springer Series in Optical Sciences, Springer-Verlag 1984.

The invention, in regard to its various aspects, with preferred embodiments also being the subject-matter of the further claims, is described hereinafter by means of Examples and Figures.

In that respect in the Figures which have already been in part described :

Figure 1a	shows a view in cross-section through a waveguide of conventional kind,
Figure 1b	is a view corresponding to Figure 1a of a waveguide with cover layer,
Figure 2	is a diagrammatic perspective view of a portion of a waveguide to describe a structuring provided in the waveguide layer or substrate for coupling-in light,
Figures 3 and 4	are diagrammatic perspective views of waveguides, with spatial structuring,
Figure 5	is a view corresponding to Figure 3 or Figure 4 showing structuring with a "buried" waveguide,
Figures 6 and 7	are a plan view and a view in section of waveguides with more complex structuring,
Figure 8	is a diagrammatic view showing energy

distributions or oscillation modes which occur for example on an asymmetrical waveguide in accordance with "Integrated Optics: Theory and Technology", Robert G. Hunsperger, Second Edition, Springer-Verlag 1984, page 36,

Figure 9 is a cross-sectional view of a waveguide according to the invention,

Figure 10 is a diagrammatic view of a waveguide structure for defining its absorption or attenuation,

Figures 11a to 11f show various possible refractive index variations plotted in relation to the thickness dimension on waveguides according to the invention, and

Figure 12 shows in relation to the thickness dimension of a silicon dioxide intermediate layer provided in accordance with the invention the relative losses in dB on the resulting waveguide according to the invention and at the layer thickness 0 the losses thereof without an intermediate layer provided in accordance with the invention.

To explain the realisation which is the underlying basis of the invention Figure 8 records the mode distribution on an asymmetrical waveguide comprising the waveguide layer 1, the substrate 2 and the cover 3. The field distribution of the two recorded modes is clear therefrom. It will be seen that the field or light energy is propagated not only in the wave-conducting layer 1, but also in the adjacent media, namely in the cover and the substrate. The percentage proportion of the energy which occurs outside the waveguide layer 1 depends inter alia on the thickness

of the waveguide layer 1 and also the refractive indices n_C, n_F, n_S, the mode type (TE, TM) and the mode number. In the case of thin waveguide layers th energy proportion which occurs as a percentage in the substrate is greater than in the case of thicker layers. Thin layers however are of outstanding interest in particular for certain uses in the sensor art.

Figure 10 shows by way of example superposed layers or phases A to D. The losses A (dV) in a volume element dV shown as a disk in Figure 10 is defined as the volume integral of the local light intensity $I(\bar{r})$ and a general loss coefficient $\alpha(\bar{r})$ which inter alia takes account of local absorption and diffusion. Accordingly the following applies in regard to the losses :

$$A(dV) = \int_{dV} I(\bar{r})\alpha(\bar{r})d\bar{r}$$

wherein $\bar{r}$ denotes the radius vector.

It will be seen therefrom, looking back at Figure 8, that the total losses of a waveguide as shown in Figure 8 increase in proportion in particular to the increasing loss value α in the substrate but in particular at the substrate/waveguide interface and in proportion to the percentage amount of energy which occurs in particular however at the substrate/waveguide interface.

While wave-conducting layers on glass, for example on Corning 7059 overall have very low losses or a very low level of absorption, the losses of the same wave-conducting layers on organic material as a substrate material, such as in particular polymer substrates, for example on polycarbonate substrates, are higher at least by a factor of 10, in dependence on the thickness of the waveguide layer 1 and accordingly the percentage proportion of energy which occurs in the substrate material but in particular at

the substrate/waveguide interface.

In that respect the above-mentioned increase in losses is not only a consequence of the respective coating process specifically employed but also a consequence of the interaction, discussed with reference to Figure 8, of the substrate material and the wave-conducting layer.

Figure 9 shows the structure of a waveguide according to the invention. It comprises a substrate 2 of organic material, in particular a polymer such as for example polycarbonate. The waveguide layer 1 is separated from the substrate 2 by at least one intermediate layer 8.

In accordance with the invention, the intermediate layer 8 and possibly an intermediate layer system 8 provides that light intensity I in the waveguide is low where the general loss coefficient α is high, whereby the losses are minimised. That is achieved by providing for a suitable configuration of the refractive index profile on the waveguide normal to the surface thereof.

Materials

1. Materials for the wave-conducting layer 1:

The following are preferably used in particular for the wavelength range of 400nm to 1000nm:

TiO_2, Ta_2O_5, ZrO_2, Al_2O_3, SiO_2-TiO_2, HfO_2, Y_2O_3, Nb_2O_5, silicon nitride, oxynitride (SiO_xN_y, HfO_xN_y, AlO_xN_y TiO_xN_y, TaO_xN_y) and MgF_2, CaF_2.

For wavelengths > 1000nm silicon, SiO_x, Ge, GaAs and GaAlAs preferably fall to be considered.

2. Substrate:

Organic materials, in that respect in particular polymers such as polycarbonate, PVC, polymethylmethacrylate (PMMA), and PET.

3. Material of the at least one and preferably the one intermediate layer 8:

Inorganic dielectric materials, in particular oxides, nitrides, carbides and the mixed forms thereof such as in particular SiO_2, Si_3N_4, more generally SiO_xN_y, and mixed materials, in particular with an SiO_2-component, an Si_3N_4-component or, more generally, an SO_xN_y-component.

4. Cover:

All known techniques with exposed waveguide layer or waveguide layer covered with a cover layer.

Processing procedures:

1. Application of the waveguide layer

Preferably vacuum coating processes are used for this purpose, in particular plasma-enhanced CVD-processes (PECVD), CVD-processes, reactive PVD-processes, in particular reactive vapour deposit, sputter coating and ion plating. The plasmas used are DC- or AC-fed, which includes low-frequency HF- and microwave plasmas and DC+AC-mixed forms. It is also possible to use non-vacuum coating processes such as for example dip drawing and spin coating.

Having regard to the fact that the at least one wave-conducting layer 1 is to be applied to the substrate material used in accordance with the invention, coating processes are preferably used in which the substrat temperature is lower than the softening temperature of the

substrate material employed, in particular < 100°C, preferably < 60°C.

2. **Application of the at least one intermediate layer:**

The same methods are used as for applying the waveguide layer, with the same limitations in regard to substrate temperature control. It is additionally possible to use plasma polymerisation if for example a silicon-containing monomer is used for the layer deposit operation.

3. **Substrate:**

The substrate of organic material, by far and away preferably a polymer, is shaped by means of a process which is known for processing plastics material. That includes in particular embossing, deep drawing, injection moulding and blow moulding (for PET-plastics).

Besides the optical function, namely providing for light intensity at an optimum low level in substrate material or at a substrate/layer interface, with a high level of absorption, the intermediate layer used in accordance with the invention or a layer of the intermediate layer system used in accordance with the invention acts as a bonding layer between the substrate on the one hand and the superposed layers. It is entirely possible to provide, towards the waveguide layer, a first intermediate layer which principally provides the desired optical insulation effect, and to solve the adhesion problem by means of a further intermediate layer, bearing against the substrate.

The losses at a waveguide according to the invention are of the same order of magnitude as the losses on conventional waveguides of glass substrate, and are in particular less than 100dB/cm, preferably less than 50dB/cm and in particular even lower than 10dB/cm.

Mor over a fact of extraordinary importance is that the provision of the interm diate layer 8 in accordance with the invention, as shown in Figure 9, means that the properties of the waveguide layer 1 are decoupled from those of the substrate 2. That affords the possibility, which is utilised in accordance with the invention, of using different waveguide layer materials on a substrate of a given material depending on the respective purpose of use involved (wavelength, mode), without the correspondingly varying interactions between the waveguide layer material and the substrate material having to be taken into consideration to a substantial degree. That also makes it possible to select in particular polymer materials which are to satisfy other criteria than optical criteria, as the substrate material.

As was made clear, the structurings shown by way of example in particular in Figures 2, 3 and 4 to 7 can be easily effected with the substrate material which is provided in accordance with the invention, and maintenance of the good optical properties which are known from the use of glass substrate is ensured by the provision of the intermediate layer in accordance with the invention.

Figures 11a to 11f show preferred refractive index profiles in relation to the thickness dimension z of the waveguide according to the invention. Therein the identification "ZS" denotes "intermediate layer", the identification "S" denotes "substrate" and the identification "F" denotes the "waveguide layer".

In regard to establishing the refractive index or the refractive index variation by way of the intermediate layer which is provided in accordance with the invention, corresponding to its thickness dimension D_{ZS}, there are various possible alternatives, as can be seen from these Figures. In most cases the refractiv index of the intermediate layer is chosen to be lower than that n_F of the

wav guide layer. As is clear from Figures 11b, 11d, 11e and 11f, it is readily possible for the configuration of the refractive index to be formed with a gradient, in particular in the intermediate layer or the intermediate layer system. That variant is preferably to be adopted when the intermediate layer is applied by plasma polymerisation.

In this respect, Figure 11f shows two possibilities whereby the refractive index of the intermediate layer, starting from the refractive index of the substrate material n_S, rises or falls. It is further shown therein that a refractive index gradient can be provided, for example by virtue of a diffusion zone, in the interface region between the intermediate layer and the waveguide layer. The thickness of the intermediate layer is preferably such that only a negligible proportion of the light energy I passes into the high-loss zone of the substrate/waveguide interface.

When a layer of inorganic material, more specifically waveguide layer material, is directly applied to an organic substrate material, in particular a polymer material, there is a high level of probability that reactions occur between components of the polymer and those of the applied wave-conducting layer. There is a high level of probability that this reaction results in a high-absorption transitional phase. This is if the waveguide were applied directly to a polymer substrate.

In accordance with the invention however, because of the similarity between the inorganic intermediate layer material and the waveguide layer material, such an interface reaction occurs to a much lesser degree, and any interface reaction between the intermediate layer material and the substrate material results only in low losses because the intermediate layer ensures that only low light energy values lead to losses at all at that interface.

Therefore the intermediate layer according to th invention does not suppress the above-m ntioned interface reaction at the substrate surface, but in practice a glass intermediate layer is simulated between the substrate and the waveguide layer. Unwanted surface roughnesses at the substrate used in accordance with the invention are smoothed out to a certain degree by the provision of the intermediate layer according to the invention, in dependence on the coating parameters.

A waveguide with the refractive index profile was produced in principle as shown in Figure 11c, under the following conditions. The substrate material used was polycarbonate with a refractive index n_s = 1.538. The intermediate layer material used was SiO_2 while the material of the waveguide layer was TiO_2. The waveguide was not covered but air acts as the cover medium.

Process parameters for TiO_2-waveguide on a PC7-substrate with an SiO_2-intermediate layer:

Intermediate layer coating process:

Sputter coating with plasma production from a DC-source whose output is temporarily cyclically separated from the plasma discharge section and the latter is temporarily short-circuited.

Target:

Target:	Ak525;SiS23379
Magnetron:	MC-525
Distance between target and substrate:	70mm
DC-source:	10kW
Vacuum chamber:	BAK-760S
Argon pressure:	pAr = 4E-3mbar
Set discharge power:	P = 6kW
DC-voltage in the metal mode:	Usb = -695V

DC-voltage in the transition mode:	Usb = -595V
Argon flow:	qAr = 58.8sccm
O_2-flow:	qO_2 = 47sccm
SiO_2-layer thickness:	varying as shown in Figure 12
Sputter rate:	R = 0.28nm/s

Production of the waveguide layer:

By means of sputtering as for the production of the intermediate layer.

Target:	Ak525;TI92-421/1
Magnetron:	MC-525
Distance target/intermediate layer-coated substrate	70mm
DC-source:	10kW
Vacuum chamber:	BAK-760S
Argon pressure:	pAr = 4E-3mbar
Plasma discharge power:	P = 6kW
DC-voltage in the metal mode:	Usb = -531V
DC-voltage in the transition mode:	Usb = -534V
Argon flow:	qAr = 57.4sccm
Oxygen flow:	qO_2 = 17sccm
Thickness of the TiO_2-waveguide layer:	95nm
Sputter rate:	R = 0.069nm/s

Taking the resulting waveguide, the losses found were about 8dB/cm in the TM-mode and at a wavelength of 633nm, with a thickness d SiO_2 of 20nm.

Figure 12 records the relative losses in dB in relation to the thickness d of the SiO_2-intermediate layer. An improvement of about a factor of 2 is already achieved with an intermediate layer thickness of 5nm. It will be clear therefrom that, with a vanishing intermediate layer, the losses increas by about a factor of 4, compared to the losses with the provision of an intermediate layer of 10nm.

It is therefor also proposed that preferably the intermediate layer should be provided in accordanc with the invention with a thickness of $\geq$ 10nm, and in that respect, as will be readily apparent, as thin as possible in order to minimise the production costs, that is to say preferably about 10 nm.

Claims

1. An optical waveguide having at least one waveguide layer on a substrate characterised in that the substrate, at least towards the waveguide layer, comprises organic material, and provided between the substrate and the waveguide layer is at least one intermediate layer which reduces the attenuation of wave propagation caused by the substrate/layer interface at least with a given mode of propagation and at least at a given wavelength.

2. An optical waveguide according to claim 1 characterised in that the organic material is a polymer, preferably polycarbonate, and/or the refractive index of the intermediate layer or an intermediate layer which lies directly against the waveguide layer is lower than that of the waveguide layer.

3. An optical waveguide according to one of claims 1 and 2 characterised in that the at least one or a further intermediate layer acts as a bonding layer in relation to the substrate.

4. An optical waveguide according to one of claims 1 to 3 characterised in that the at least one or a further intermediate layer which bears against the waveguide layer at the substrate side has a substantially lower level of propagation attenuation than further intermediate layers disposed at the substrate side or the substrate itself.

5. An optical waveguide according to one of claims 1 to 4 characterised in that it is spatially structured, preferably the substrate is embossed, deep-drawn or injection-moulded.

6. An optical waveguide according to one of claims 1 to 5 characterised in that its attenuation is lower at least by a factor of 3 than without the at least one intermediate

layer.

7. An optical waveguide according to on of claims 1 to 6 characterised in that the waveguide layer material, in particular for wavelengths of 400nm to 1000nm, comprises at least one of the following materials:

TiO_2, TaO_5, ZrO_2, Al_2O_3, SiO_2-TiO_2, HfO_2, Y_2O_3, Nb_2O_5, silicon nitride, oxynitride (SiO_xN_y, HfO_xN_y, AlO_xN_y TiO_xN_y, TaO_xN_y) and MgF_2, CaF_2,

and preferably for wavelengths > 1000nm at least one of the following materials:

silicon, SiO_x, Ge, GaAs, GaAlAs.

8. An optical waveguide according to one of claims 1 to 7 characterised in that its attenuation is of the same order of magnitude as with a waveguide of the same waveguide layer material on a glass substrate, being preferably lower than 100dB/cm, preferably lower than 50dB/cm, and preferably even lower than 10dB/cm.

9. An optical waveguide according to one of claims 1 to 8 characterised in that the at least one intermediate layer comprises an inorganic material, preferably a material with silicon oxide, such as SiO_2, or an SiO_2, TiO_2-mixture or a material with Si_3N_4, such as Si_3N_4 or a mixture with Si_3N_4, wherein same is of a thickness of at least 5nm, preferably a thickness of at least 10 nm.

10. A process for the production of an optical waveguide comprising the following steps:

a) shaping a substrate from organic material;

b) applying at least on intermediate layer by a vacuum coating process; and

c) applying a wave-conducting layer.

11. A process according to claim 10 characterised in that the shaping operation comprises embossing, deep-drawing or injection moulding of a substrate from a polymer, preferably polycarbonate, and/or is effected on a substrate with at least one or a further intermediate layer already applied thereto, as a bonding layer in relation to the substrate.

12. A process according to one of claims 10 and 11 characterised in that the intermediate layer is produced by a PECVD- or a reactive PVD-process or plasma polymerisation and in that operation preferably at least one intermediate layer of inorganic material is deposited, preferably with SiO_2 and/or Si_3N_4.

13. A process according to one of claims 10 to 12 characterised in that the waveguide layer is produced by a reactive PVD-process, in particular by ion plating.

14. A process according to one of claims 10 to 13 characterised in that the operation of applying the intermediate layer and the operation of applying the waveguide layer are effected at substrate temperatures of at most 100°C and preferably at most 60°C.

15. Use of an intermediate layer between a wave-conducting layer of a waveguide and a carrier substrate for decoupling of the properties of the wave-conducting layer and the substrate.

16. Use of a substrate of organic material, in particular a polymer, as a carrier substrate for selectively applied waveguide layers by means of the provision of at least one intermediate layer between the substrate and the wav-guide layer.

17. An optical waveguide constructed, arranged and adapted to operate substantially as herein described with reference to, and as shown in, the accompanying diagrammatic drawings.

Patents Act 1977 **Examiner's report to the Comptroller under Section 17** **(The Search report)** 19	Application number GB 9413594.4
Relevant Technical Fields (i) UK Cl (Ed.M) G2J (JGDA); C7F (FPCL, FPDL, FPCX, FPDX, FBAL, FBAX, FBBL, FBBX, FBXL, FBXX) (ii) Int Cl (Ed.5) G02B; C23C	Search Examiner MR C J ROSS Date of completion of Search 23 AUGUST 1994
Databases (see below) (i) UK Patent Office collections of GB, EP, WO and US patent specifications. (ii) ONLINE DATABASE WPI	Documents considered relevant following a search in respect of Claims :- 1-17

Categories of documents

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Category	Identity of document and relevant passages		Relevant to claim(s)
X,Y	GB 1282941	(PLESSEY) see especially page 1 line 47	X: 15 Y: 10
Y	EP 0336421 A2	(MITSUBISHI) see especially page 4 line 6 on	1, 15, 16
X,Y	EP 0323317 A1	(C.A.L'.E.A) see especially column 1 line 33 and column 2 line 15 on	X: 15 Y: 1, 10, 16
X	EP 0228886 A2	(AT & T)	15
X	EP 0194639 A2	(KURARAY)	1, 15, 16

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